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Monitoring Systems of Agricultural Soils Across Europe Regarding the Upcoming European Soil Monitoring Law

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ABSTRACT

In Europe, 60%–70% of soils are considered degraded, underscoring the urgent need for consistent monitoring to prevent further degradation and support evidence-based policies for sustainable soil management. Many countries in Europe have implemented one or more soil monitoring systems (SMSs), often established long before the EU-wide "Land Use/Cover Area frame statistical Survey Soil", LUCAS Soil program. As a result, their sampling strategies and analytical methodologies vary significantly. The proposed EU Directive on Soil Monitoring and Resilience (Soil Monitoring Law, SML) aims to address these differences by establishing a unified framework for systematic soil health monitoring across the EU. This paper assesses the compatibility of the 25 identified SMSs from countries participating in the EJP SOIL Program with the anticipated requirements of the SML. The analysis focuses on critical aspects, including sampling strategies, analytical methods, and data accessibility. Results show significant variability in SMS approaches, including sampling depth, monitored land uses, and analytical methods, which limit cross-system comparability. Despite challenges, opportunities for harmonization include aligning SMSs with the LUCAS Soil methodology, developing transfer functions, and adopting scoring systems for soil health evaluation. Enhanced collaboration and data accessibility are also emphasized as critical for achieving the SML's objectives. This research provides actionable recommendations to harmonise SMSs with the SML framework, promoting coordinated soil monitoring efforts across Europe to support the EU's goal of achieving healthy soils by 2050.

1 | Introduction

Life on Earth fundamentally relies on healthy soils. Soil health—defined as "the physical, chemical, and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services" (European Commission 2023)—is crucial for maintaining ecological balance and supporting human well-being (Veerman et al. 2020). However, soils are increasingly under threat in Europe, with an estimated 60%–70% of European soils classified as somewhat degraded or unhealthy by 2020 (Panagos, Borrelli, et al. 2024). This highlights an urgent need for reliable and consistent data on soil to evaluate soil health, particularly for practitioners and policymakers striving to detect soil degradation at an early stage and promote sustainable soil management practices (De Richer Forges and Arrouays 2010). While a qualitative definition of soil health exists, the lack of a widely accepted quantitative framework—such as measurable indicators with respective threshold values—poses a significant challenge (Lehmann et al. 2020). This gap complicates the translation of the concept into actionable criteria for monitoring and management. Soil monitoring systems (SMSs) are essential for the systematic assessment of soil properties, enabling the detection of spatial and temporal changes (FAO/ECE 1994). The design of a SMS involves several key decisions: (i) determining the appropriate timing and frequency of sampling; (ii) selecting sampling locations in order to well represent the soil variability, land uses and land management; (iii) specifying the sampling depth and methodology, including whether to sample by pedogenic horizons or fixed depth increments, the tools used, and the collection of a single or composite sample; (iv) deciding which soil properties to analyze and the methods for sample preparation and laboratory analysis; and (v) defining the relevant metadata (e.g., climate and land management) and data to be collected to allow for the accurate interpretation of the results.

Most EU Member States have designed and established one or more SMSs within their countries, though the specifics of these SMSs differ between countries. Several studies underlined the challenges in comparing and sharing data between SMSs, either due to technical discrepancies (e.g., differences in sampling strategies, analytical methods, and data format) but also due to costs and legal requirements (Morvan et al. 2008; van Leeuwen et al. 2017; Cornu et al. 2023; Froger et al. 2024; Meurer et al. 2024). In parallel, the Joint Research Centre of the European Commission (EU-JRC) developed its own SMS, LUCAS Soil, to report on the state of soils across Europe (Orgiazzi et al. 2018). LUCAS Soil was designed to offer a unified, standardized approach to the collection and analysis of topsoil samples throughout the EU, with results now displayed on the EU Soil Observatory (EUSO) Soil Health Dashboard accessible through the European Soil Data Centre (ESDAC) (Panagos, Broothaerts, et al. 2024). However, recent findings by Froger et al. (2024) reveal significant differences between LUCAS Soil and national SMSs, with the latter generally covering a broader range of land covers, soil types, and regions. Key soil properties, including pH, soil organic carbon, nutrients, and clay content, also showed marked differences between data from LUCAS Soil and national SMSs when analyzed on a national scale. Therefore, LUCAS Soil cannot be used as the only EU SMS but should be complemented by national SMSs, which underscores the critical need for harmonizing SMSs across EU Member States to achieve comparable evaluations of soil health at the European level.

This need for harmonization aligns with broader European objectives to safeguard soil. Central to these efforts is the EU Soil Strategy for 2030 (European Commission 2021), which aims to ensure that all EU soils are in healthy condition by 2050. To support this goal, the European Commission proposed the Soil Monitoring and Resilience Directive (European Commission 2023), commonly referred to as the Soil Monitoring Law (SML). This directive aims to establish a unified legal framework to enable systematic monitoring of soil health on all land uses across Member States while promoting sustainable soil management practices. One objective is to achieve a coordinated and standardized soil monitoring approach across Europe, enabling consistency, comparability, and transparency in soil data collection. The proposed directive sets forth specific requirements for soil sampling and analysis to address existing differences and enable harmonized soil health assessments in all Member States (European Commission 2023). This raises a critical challenge: how do current SMSs reflect the principles outlined in the SML? Additionally, what updates are needed to further enhance their contribution to a unified European soil monitoring framework, having in mind that most Member States have indicated that they do not want to significantly modify their current SMSs (Bispo et al. 2021).

By examining 25 SMSs from 24 countries participating in the European Joint Program for Soil (EJP SOIL; www.ejpsoil.eu), and the EU-level LUCAS Soil, this research aims to: (i) compare existing SMSs focused on agricultural soils; (ii) examine the extent to which these SMSs reflect the proposed SML's objectives; (iii) identify potential challenges or areas where current SMSs could evolve to support the SML's implementation; and (iv) evaluate the feasibility of standardization (all countries apply the same protocols) or harmonization (a way to stitch varying practices together) of SMSs across the EU, and propose actionable recommendations. Although LUCAS Soil is included in the analysis to illustrate technical aspects

Summary

- Identifies gaps between EU soil monitoring systems (SMS) and upcoming Soil Monitoring Law (SML).
- Provides the first comparative analysis of 25 SMSs vs. proposed SML criteria.
- Reveals key differences in sampling strategies, measured parameters, and data access across SMSs.
- Proposes practical solutions for harmonizing SMSs while respecting national contexts.

or existing collaborations, it is not used as a benchmark. This paper provides a foundation for guiding the implementation of the SML and advancing coordinated soil monitoring practices across Europe.

2 | Materials and Methods

2.1 | Design and Implementation of a Survey to Report SMSs

A web-based survey was conducted to review SMSs focusing on agricultural soils (other land uses being potentially also included) across the EJP SOIL countries (Bispo et al. 2021). Experts from each of the 24 participating countries (Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, the Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, and United Kingdom), as well as the EU-JRC, were invited to complete the online survey. The survey was designed to gather detailed information about the agricultural or general SMSs present in each of the EJP SOIL countries, focusing on the sampling protocols and the soil analytical methods, to identify similarities and differences. The survey started with questions to identify the name, objectives, and land-use scope of each SMS. Second, experts were asked for information on the temporal and spatial sampling protocols used in the SMSs. Third, details on the properties measured and the soil analysis methods employed were asked for. Fourth, stakeholders familiar with the topic were asked to provide insights into potential harmonization options, indicating which aspects of their protocols could be adapted or modified. Finally, experts were asked to indicate their willingness to collaborate with LUCAS Soil, to modify their existing SMS protocols, or to add new monitoring sites. It is important to note that these experts were scientists. Their views, therefore, do not represent official national positions.

Following a pretest phase and subsequent adjustments, the survey was launched in April 2021 and remained open for 2 months, closing in June 2021. It was administered via an online survey platform. After data collection, thorough data cleaning was conducted to identify and correct any errors or omissions. Clarifications were sought from country experts when needed, and terminologies were standardized to ensure comparability across SMSs. In August 2024, the survey was newly expanded to allow countries to verify and complete any missing information related to their SMS. Additional questions were included to gather details on the methods used to measure soil properties and to determine whether any new or previously overlooked SMS should be added. In addition to survey responses,

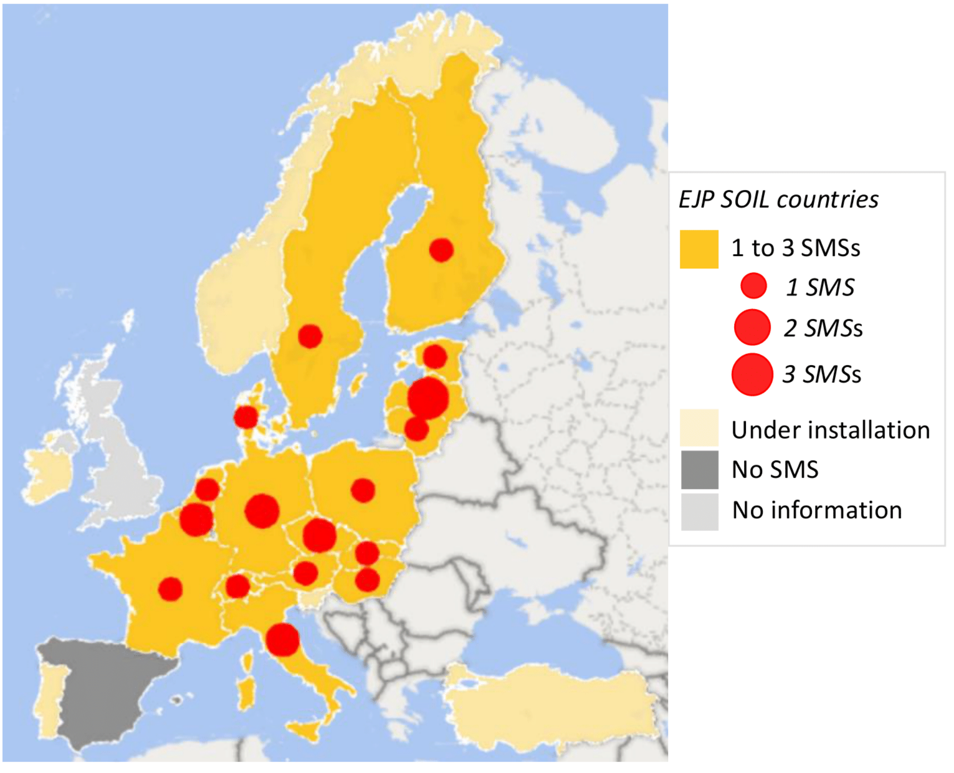

FIGURE 1 | Geographical distribution of SMSs included in the survey conducted across EJP SOIL countries. LUCAS Soil for the EU is not represented.

complementary information was extracted from existing sources (Froger et al. 2024; Götzinger and Sandén 2024).

2.2 | Reported SMSs

A total of 29 existing SMSs, including LUCAS Soil for the EU, were reported across 18 countries and the EU (Figure 1). These countries include Austria, Belgium, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, the Netherlands, Poland, Slovakia, Spain, Sweden, and Switzerland. To be included in this study, each SMS had to meet specific criteria. While the SML addresses all types of land use, EJP SOIL narrows its scope to agricultural soils. Consequently, this study excludes SMSs that focus solely on other land uses (e.g., the Swedish Forest Soil Inventory and the Forest Soil Monitoring in Estonia). However, it is important to note that some of the reported SMSs encompass multiple land uses, including but not limited to agricultural soils, as certain countries' SMSs (e.g., France) do not have separate surveys for different land uses. For such SMSs, the reported data (e.g., monitored surface area per site) refer to the entire monitoring network, not exclusively to agricultural soils. Additionally, at least one monitoring campaign must have been conducted, with future measurements planned if only one campaign has occurred (excluding Spain due to a lack of follow-up measurements) (Morvan et al. 2008).

It is important to note that Portugal, Turkey, Norway, and Slovenia reported not having an SMS in place, though negotiations are ongoing to establish one (e.g., in Portugal and Norway). Similarly, Ireland has initiated a national inventory but has yet to fully implement an SMS. No data were collected from the United Kingdom. Additionally, in some countries, soil monitoring is conducted at the sub-national level under the jurisdiction of regional authorities (e.g., Austria, Belgium, Germany, and Italy). Some countries also operate multiple SMSs focused on different soil properties, as is the case in the Czech Republic, Germany, Belgium, and Latvia. After applying the inclusion and exclusion criteria, we were left with 25 SMSs from 17 of the 24 countries participating in EJP SOIL, along with LUCAS Soil at the EU level. Since not all SMSs responded to every question in the survey, the number of SMSs considered in the analysis may vary between questions. Percentages are therefore calculated based on the subset of SMSs that provided relevant answers.

3 | Results

3.1 | Comparative Analysis of Sampling Strategies in Relation to the SML

3.1.1 | Sampling Design

The spatial distribution of sampling sites is a critical component in the design of SMSs. One of the adjusted proposals for the SML specifies that the sampling approach should follow a stratified random scheme, where the strata are defined as soil units, being the combination of soil type and land use. These soil units are sampled, and the results have to be reported at the soil district level, which is are operational or administrative strata consisting of multiple soil units. These soil districts are to be defined by each Member State. They could, for example, correspond to Nomenclature of Units for Territorial Statistics (NUTS) level 1 or 2. In addition, "the number and location of the sampling points shall represent the variability of the chosen soil parameters within the soil units with a maximum percent error of 5%". An analysis of the reported SMSs reveals varying levels of compatibility with these sampling design requirements:

1. The sampling design of the different SMSs follows either a grid-based design, a stratified approach, or a combination of both. The stratified approach is used by 61% of SMSs (14 out of 23) (Table 1). In these cases, site selection is primarily based on soil-related characteristics (such as soil type, texture, classification, and pedological regions), often in combination with other criteria. For example, site selection considers land use and climatic conditions (Czech Republic_BMP); geographical and soil characteristics (e.g., parent material, soil types and formation) (Hungary), as well as land use (Germany_BD); soil types and texture (Poland and Latvia_nitrogen); soil type, farming type (biological, conventional) and production (horticulture, arboriculture, animal), and territorial division (Latvia_agro and Latvia_carbon); with the notable exception of Belgium_Flanders that is only based on land use. A regular grid sampling approach is used by 26% (6 out of 23) of the SMSs, with cell sizes varying between SMSs, ranging from 4 km × 4 km (Austria) to 16 km × 16 km (France). Finally, 13% (3 out of 23) of the SMSs (LUCAS Soil, Finland, and Slovakia) have a combination of both designs. In LUCAS Soil, site selection is first based on a regular grid, but the choice of the cells within that grid to be sampled is then stratified according to land cover type, defined by the area-frame, and does not consider soil type. This raises the question of whether the number of samples is sufficient to accurately represent/cover the diversity of soil units within each SMS. There is no universally optimal design; sampling strategies should be adapted to the indicators, expected outputs, and required precision. Within the SML framework, which relies on soil units, stratified sampling is generally more appropriate, though its advantage diminishes with increasing sampling density.
2. The SML mandates soil monitoring across all land use types, including agricultural, forested, natural, and urban areas. Based on the scope of this study, which focuses on SMSs related to agricultural soils, 48% of the current SMSs monitor a large range of land uses, while 52% (13 out of 25) focus exclusively on agricultural soils (Table 1). It is important to note that this analysis does not account for SMSs dedicated solely to other land uses, such as forest soils (e.g., BZE-Forest in Germany or the Swedish Forest Soil Inventory). While some countries operate separate SMSs for different land uses, this separation can lead to greater heterogeneity in soil health assessment and complicate comparisons across land uses, even within a country.
3. Our analysis reveals a significant variation in the number of sampling sites per SMS, ranging from 30 sites in Estonia to 420,000 in the Czech Republic_AZZP (Table 1). To enable comparisons, the number of sites was normalized to

TABLE 1 | Description of the reported SMSs, categorized by the: (i) monitoring objectives, where pH represents pH and nutrients monitoring, SOC soil organic carbon monitoring, and O overall state of the soil (including SOC, pH, and nutrients); (ii) aggregated data accessibility, where Yes indicates data freely available, No indicates data not yet available or restricted, and Req indicates data available upon request; (iii) availability of soil management data; (iv) temporal sampling, including the starting year, whether the SMS is still operational, and the interval between campaigns (in years); and (v) spatial sampling, including the number of sampling sites, the sampling design type (Strat = stratified representative sites, Grid = sampling based on a regular grid, Mix = combining both stratified and grid-based approaches), the monitored land uses (All = several or Agri = agricultural), the sampling depth type (one or several fixed, or depth according to soil horizons), and the number of samples per depth in a composite sample.

	General description				Temporal sampling			Spatial sampling				
Countries/SMSs	**Name of the SMS**	**Aim**	**Data access**	**Management data**	**Starting year**	**Still running**	**Interval (years)**	**Number of sites**	**Design type**	**Land uses**	**Depth type**	**Number samples**
Austria	Soil inventories of the Austrian federal provinces (BZIs)	O	Req	No	1990	Yes	≈10	2000	Grid	All	Several	12–20
Belgium_Flanders	Flemish soil organic carbon monitoring network (Cmon)	SOC	No	Yes	2021	Yes	10	2594	Strat	All	Several	7–16
Belgium_Wallonia	Total soil organic carbon (CARBIOSOL)	SOC	Yes	Yes	2004	No	10	590	Strat	Agri	Horizons	5
Belgium_requa	REQUASUD	O	Yes	Yes	2005	Yes				All	Horizons	25
Czech Republic_AZZP	Agrochemical soil testing network (AZZP)	O	Req	No	1962	Yes	≈6	420,000		Agri	One	30
Czech Republic_BMP	Basal soil monitoring (BMP)	O	Req	No	1992	Yes	6	214	Strat	Agri	Several	6
Denmark	Danish national square grid (NSG_agro)	SOC	No	Yes	1986	Yes	≈10	573	Grid	All	Several	10
Estonia	Agricultural soil monitoring	O	Yes	Yes	1983[a]	Yes	5	30	Transect	All	Horizons	
Finland	Monitoring of arable soil chemical quality (Valse)	O	No	Yes	1974	Yes	≈10	630	Mix	Agri	One	10–20

(Continues)

TABLE 1 | (Continued)

	General description				Temporal sampling			Spatial sampling				
Countries/SMSs	Name of the SMS	Aim	Data access	Management data	Starting year	Still running	Interval (years)	Number of sites	Design type	Land uses	Depth type	Number samples
France	Soil Quality monitoring network (RMQS)	O	Yes	Yes	2000	Yes	≈15	2241	Grid	All	Several	25
Germany_BZE-LW	Agricultural soil condition survey (BZE-LW)	SOC	Yes	Yes	2011	Yes	≈10	3104	Grid	Agri	Several	30
Germany_BD	Permanent soil monitoring in Germany (BD)	O	No	Partly	1985	Yes	4–5	800	Strat	All	Horizons	15–20
Hungary	Hungarian soil information and monitoring system (TIM)	O		Yes	1992	Yes	1	1236	Strat	All	Several	1
Italy_Lombardia	Regional soil nutrients monitoring network	pH	Req	No	2010	Yes	1	120	Strat	Agri	Several	5
Italy_Veneto	ARPAV_UOQS	O	Yes	Yes	2012	Yes	5 or 1[b]	100	Strat	All	One	3 or 16[b]
Latvia_agro	Soil agrochemical research—representative sample frame	O	Yes	Yes	2018	Yes	1	6250	Strat	Agri	One	10–20
Latvia_nitrogen	Mineral nitrogen monitoring	pH	Yes	Yes	2006	Yes	1	48	Strat	Agri	Several	10
Latvia_carbon	SOC monitoring in representative sample frame	SOC	Yes	Yes	2018	Yes	1	100	Strat	Agri	Several	5
Lituania	Monitoring of soil agrochemical properties	O	Yes	Yes	1993	No	10	10,000	Strat	Agri	One	15–20

(Continues)

TABLE 1 | (Continued)

	General description				Temporal sampling			Spatial sampling				
Countries/SMSs	Name of the SMS	Aim	Data access	Management data	Starting year	Still running	Interval (years)	Number of sites	Design type	Land uses	Depth type	Number samples
Netherlands	Netherlands Soil Sampling Program (CC-NL)	O	No	No	1998	Yes	6	1392	Strat	All	Several	5
Poland	Monitoring of Arable soils of Poland (MChG)	O		No	1995	Yes	5	216	Strat	Agri	One	20
Slovakia	Partial soil monitoring system (ČMS-P)	O	Yes	No	1993	Yes	5	318	Mix	Agri	Several	3 or 5[c]
Sweden	Swedish soil & crop inventory	O	Yes	Yes	1995[a]	Yes	10	2000	Grid	Agri	One	10
Switzerland	Swiss Soil Monitoring Network (NABO)	O	Req	Yes	1984	Yes	5	114	Strat	All	One	25
LUCAS Soil	Land Use/ Cover Area frame statistical Survey Soil	O	Yes/No[d]	No	2009	Yes	3–4	25,000	Mix	All	One	5

[a]Started in 1983 until 1992, was re-established in 2002.
[b]One-year interval and 3 samples per depth for biological quality/5-year interval and 16 samples per depth for nitrates and heavy metals.
[c]Five samples for chemical analysis and three samples for physical analysis.
[d]While most data are freely accessible, access to contaminant-related data is restricted.

the monitored area, using agricultural land for SMSs focused on agricultural soils and total country surface area for SMSs covering all land uses (Figure 2). It is important to note that the monitored area may exclude non-soil-covered surfaces, such as bare rock or water bodies, which can represent a non-negligible part of a country (e.g., 17% in Switzerland). The number of sampling sites per unit area varies widely among SMSs, ranging from one site per 0.1 km^2 in the Czech Republic_AZZP to one site for over 400 km^2 in Poland, Latvia_nitrogen, or Germany_BD. This potentially depends on the aim of the SMS, for example, if results are only meant to be interpreted at the national or at subnational/regional level. According to Morvan et al. (2008), a density of one sampling site per 300 km^2 is recommended for a good coverage of a country's soil variability. However, this reference value may no longer be applicable when considering soil units as the basis, as requested by the SML.

3.1.2 | Sample Collection

The SML specifies that at least five subsamples should be collected to a depth of at least 30 cm, homogenized to create a composite sample, and data reported by fixed depth. Additionally, the SML requires that "exact sampling locations should be sampled". An analysis of the reported SMSs reveals varying levels of compatibility with these requirements:

1. Composite sampling is performed in all SMSs except in Estonia, where composite sampling is applied only for heavy metals and pesticide residues, while the main sample collection is done in soil pits. Among the SMSs conducting composite sampling, the majority (88%, 21 out of 24) collect at least five subsamples (Table 1). Exceptions include Hungary, which collects fewer subsamples, and Slovakia and Italy_Veneto, where the number depends on the soil property analyzed.
2. About half of the SMSs (12 out of 25) use multiple fixed-depth intervals, while nine SMSs sample only at one fixed depth (the topsoil), and four SMSs rely on pedogenic horizons (Table 1). For comparison issues, it is recommended to use fixed depths in order to avoid subjectivity in sampling, harmonize sampling protocols, and facilitate comparisons between SMSs and over time (Arrouays et al. 2012). However, sampling based on pedogenic horizons may better reflect soil formation processes. Ideally, both approaches should be combined, sampling by fixed depth increments in the site, and by pedogenetic horizons in soil pits dug close to the monitoring area. Among SMSs with fixed depths, sampling ranges from shallow layers (e.g., 0–10 cm) to deeper profiles up to 100 cm (Figure 3). Eleven of these SMSs are currently sampled to a depth of 30 cm, as specified in the SML. Three SMSs (both Czech Republic SMSs and Italy_Veneto) apply this depth for specific crops or soil properties, while seven SMSs (Finland, Latvia_agro, Lithuania, Poland, Slovakia, Sweden, Switzerland) use shallower sampling depths. It is worth noting that LUCAS Soil used a sampling depth of 20 cm until 2022, when it was increased to 30 cm.
3. In terms of sampling geolocation, all SMSs in this study now use GPS coordinates to ensure precise geolocation,

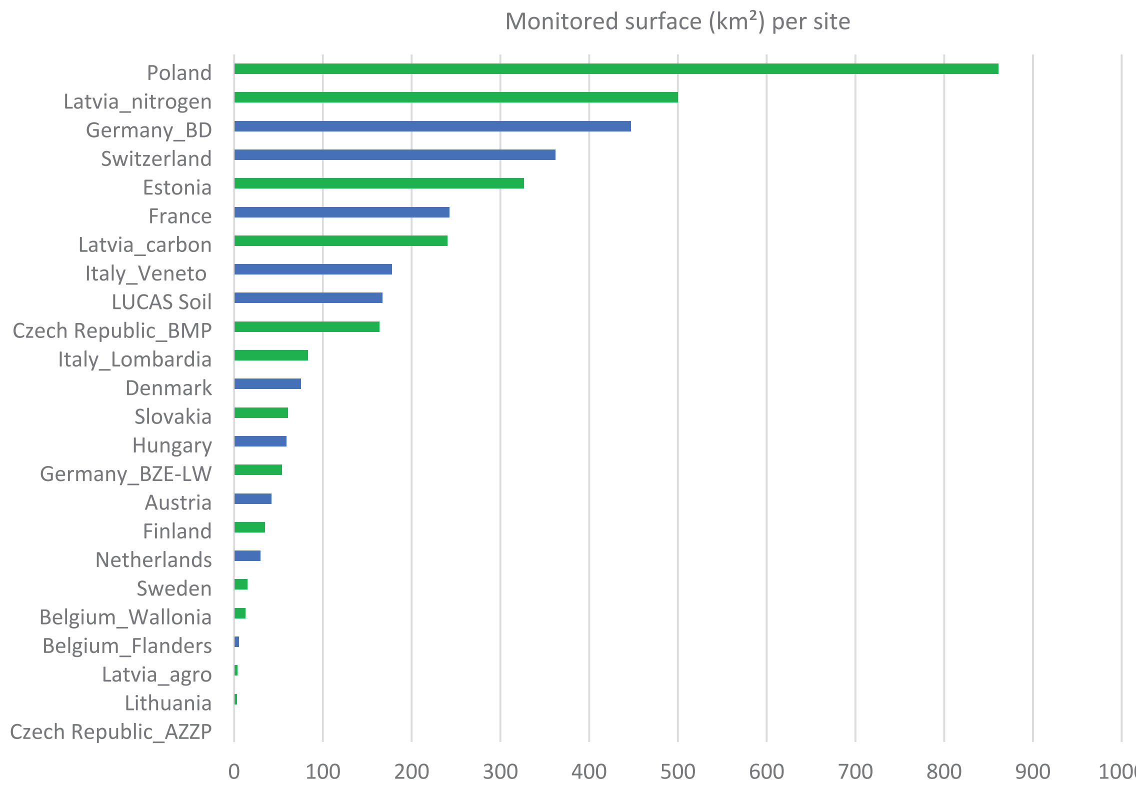

FIGURE 2 | Distribution of monitored surface area (km^2) per sampling sites across SMSs, normalized by agricultural land area for SMSs targeting agricultural soils (green) or by total surface area for SMSs with all land uses (blue).

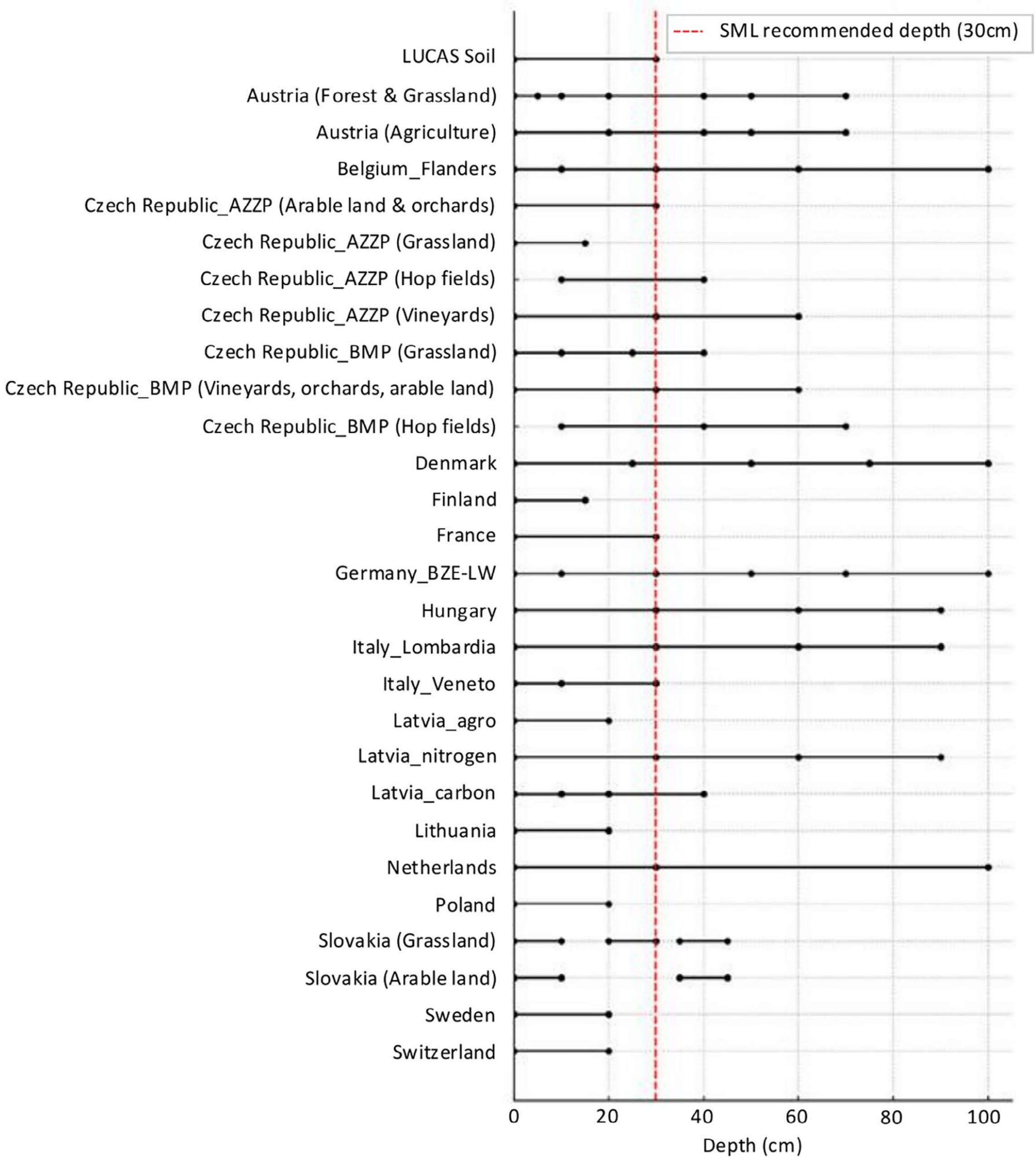

FIGURE 3 | Soil sampling depth intervals by country and land use for SMSs reporting one or more fixed soil depths. Each horizontal line represents the depth intervals specific to a given SMS, with distinctions made for different land uses where applicable. The red dashed line indicates the SML's recommended sampling depth of 30 cm. For Italy_Veneto, the one fixed depth varies: 0–10 cm for biological quality assessments, and 0–30 cm for nitrates and heavy metals. In France, for agricultural tilled or ploughed soils, the upper layer limits depend on ploughing or tilling depths; otherwise, the fixed depth is 0–30 cm. SMSs relying on pedogenic horizons are not represented in this figure.

with two exceptions: in Germany-BD, GPS use is recommended but not mandatory in all cases, and in the Netherlands, it was implemented only since the 2018 campaign, not in 1998.

3.1.3 | Sampling Time Interval

Among the 25 reported SMSs, 23 remain operational. The majority (54%, 13 out of 24) were established in or before 1995, demonstrating a long-standing commitment to soil monitoring. Two (Lithuania and Belgium_Wallonia) have however been discontinued (Table 1). Lithuania is re-establishing monitoring in 2025, and Belgium–Wallonia is developing a new SMS aligned with the SML.

The proposed SML specifies that "new soil measurements are performed every six years, within one sampling campaign or as part of a continuous sampling scheme during the indicated period of time". Sampling time intervals between repeated measurements on the same sites vary widely among the SMSs, ranging from annual to more than 15 years. Most SMSs (63%, 15 out of 24) operate within the 6-year interval suggested by the SML, including LUCAS Soil, which samples every 3–4 years. However, nine SMSs (Austria, Belgium_Wallonia, and Belgium_Flanders, Denmark, France, Finland, Germany_BZE-LW, Lithuania, and Sweden) return to the same sampling sites less frequently than every 6 years. The lack of consensus in the literature on optimal sampling intervals likely explains the variation observed between SMSs. Some (e.g., Bellamy et al. 2005) suggest reducing the interval to improve the detection of short-term changes, while others (e.g., Desaules et al. 2010) recommend adapting it to ensure that observed trends exceed methodological uncertainties. One option could be to shorten the interval but avoid analysing all soil properties in every campaign.

3.1.4 | Additional Information

In terms of field data, the SML emphasises the importance of closely monitoring the impact of soil management practices and recording the soil type. 68% of SMSs (17 out of 25) collect data on soil management practices (Table 1). This includes information gathered through interviews or surveys with farmers or land planners, covering aspects such as inter-campaign periods, the history and evolution of land use, and land management practices including crop rotations, crop management, and tillage practices. Additionally, 56% of SMSs (14 out of 25) record soil type. Among these, 11 SMSs (79%) rely on national classification standards (Belgium_Wallonia, Czech Republic_BMP, France, Germany_BZE-LW, Germany_BD, Hungary, Italy_Veneto, Lithuania, Netherlands, Slovakia, and Switzerland), 2 (14%) use the World Reference Base for Soil Resources (WRB) classification (LUCAS Soil and Denmark), and 1 (7%) records both the national standard and the WRB results (Estonia). Note that Lithuania's soil classification was harmonized with the WRB classification. This issue is particularly important, as there is no direct correspondence between national soil classification systems and the WRB. Harmonization therefore requires either extensive training of soil surveyors in the WRB or post-processing efforts to convert, when feasible, as some information may be missing.

3.2 | Comparative Analysis of Measured Soil Properties and Corresponding Analytical Methods in Relation to the SML

The list of measured soil properties varies among SMSs, reflecting their diverse objectives (Table 1). The majority (72%, 18 out of 25) aim to assess the overall state of the soil. Some SMSs (20%, 5 out of 25), such as Belgium's (Flanders and Wallonia), Denmark's, Latvia's (carbon), and Germany's (BZE-LW), particularly focus on monitoring soil organic carbon (SOC), although other soil properties are also measured. Additionally, 8% (2 out of 25) of the SMSs, namely in Latvia (nitrogen) and Italy (Lombardia), primarily monitor different forms of soil nitrogen in relation to the Nitrate Directive.

However, the SML proposes a list of specific soil properties to be analyzed, including physical, chemical, and biological properties (Table 2). Among these, soil organic carbon, particle size distribution, extractable phosphorus, carbonate content, total nitrogen content, effective cation exchange capacity, bulk density, and heavy metals are widely measured. In contrast, properties such as electrical conductivity, pH, soil organisms, and organic contaminants are only moderately measured, while soil water holding capacity and saturated hydraulic conductivity are rarely measured.

TABLE 2 | Soil properties recommended by the SML and number of SMS measuring each parameter ($n = 25$). We considered as widely measured those properties assessed by more than half of the SMSs, and as rarely measured those included in fewer than 10% of SMSs.

Soil properties monitored	Number of SMSs measuring each parameter	Frequency of measurements
pH	Water: 13, KCl: 8, $CaCl_2$: 9	Moderately
Particle size distribution	20	Widely
Effective cation exchange capacity (ECEC)	16	Widely
Electrical conductivity	9	Moderately
Bulk density	Topsoil: 15, Subsoil: 16	Widely
Soil water holding capacity	2	Rarely
Saturated hydraulic conductivity (Ksat)	2	Rarely
Organic carbon	24	Widely
Carbonate content	16	Widely
Soil organisms	8	Moderately
Heavy metals	15	Widely
Organic contaminants	6	Moderately
Total nitrogen content	16	Widely
Extractable phosphorus	18	Widely

Even among the widely measured soil properties, significant variability exists in the laboratory analysis methodologies applied across SMSs, which complicates the comparison of soil health assessments. To address these differences, the SML recommends specific reference methodologies for measuring these properties, most of which are ISO-based, although alternative methods are specified in some cases, such as for extractable phosphorus. Methodologies applied to widely monitored soil properties across SMSs are examined (Table 3). Overall, properties such as organic carbon, bulk density in topsoil, bulk density in subsoil, total nitrogen content, particle size distribution, and carbonate content show broader adoption of ISO standards compared to others, like heavy metals, effective cation exchange capacity (ECEC), and extractable

TABLE 3 | Overview of methodologies used to measure soil properties widely monitored across the SMSs, showing their alignment with ISO-recommended methods outlined in the SML. SMSs are categorized by ISO-recommended, comparable, or alternative methods, with parentheses indicating the number of SMSs per category.

Properties monitored	ISO recommended methods	SMSs using: The recommended ISO methods	SMSs using: Comparable methods	SMSs using: Alternative methods
Particle size distribution	11277	BE[3], DE[1], DE[2], DK, EE, EU, SE	IT[2]	AT, BE[1], CH, CZ[2], FI, FR, HU, IT[1], LT, NL, PL, SK
ECEC	11260	DE[1], EU, SE	AT, CH, IT[2]	BE[3], CZ[1], CZ[2], DE[2], FR, HU, IT[1], NL, PL, SK
Bulk density (Topsoil)	11272	BE[1], BE[2], DE[1], DE[2], DK, EE, FR, IT[2], LT, LV[3]	EU	AT, CH, HU, NL
Bulk density (Subsoil)	11272	BE[1], BE[2], DE[1], DE[2], DK, FR, IT[2], LT, LV[3]	EU	AT, CH, CZ[2], HU, NL, SK
Organic carbon	10694	BE[1], BE[2], BE[3], CH, DE[1], DK, EE, EU, FR, LT, LV[3], NL, SE	IT[2]	AT, CZ[1], CZ[2], DE[2], FI, HU, IT[1], LV[1], PL, SK
Carbonate content	10693	BE[3], CH, EU, DE[2], FR, NL, SK	IT[2]	AT, BE[2], CZ[1], DE[1], DK, HU, PL, SE
Heavy metals	54321[a]	AT, BE[3], IT[2]		CH, CZ[2], DE[2], EE, EU, FI, FR, HU, IT[1], PL, SE, SK
Total nitrogen content	11261/13878	BE[1], BE[3], CH, DK, EU, FR, IT[2], SE	AT, DE[1], DE[2]	CZ[2], FI, HU, IT[1], NL
Extractable phosphorus	11263[b]	EU, FR, IT[2]		AT, BE[3], CH, CZ[1], CZ[2], DE[2], EE, FI, IT[1], LT, LV[1], NL, PL, SE, SK

Abbreviations: AT, Austria; BE[1], Belgium_Flanders; BE[2], Belgium_Wallonia; BE[3], Belgium_requa; CH, Switzerland; CZ[1], Czech Republic_AZZP; CZ[2], Czech Republic_BMP; DE[1], Germany_BZE-LW; DE[2], Germany_BD; DK, Denmark; EE, Estonia; EU, LUCAS Soil; FI, Finland; FR, France; HU, Hungary; IT[1], Italy_Lombardia; IT[2], Italy_Veneto; LT, Lithuania; LV[1], Latvia_agro; LV[2], Latvia_nitrogen; LV[3], Latvia_carbon; NL, Netherlands; PL, Poland; SE, Sweden; SK, Slovakia.
[a]Heavy metals (As, Sb, Cd, Co, Cr (total), Cu, Hg, Pb, Ni, Tl, V, and Zn) should be measured using ISO 54321 digestion (with Aqua Regia), with optional analysis of bioavailable fractions using ISO 17586 (dilute nitric acid).
[b]ISO 11263 is the preferred method; nevertheless, other methods can be used as an alternative.

phosphorus. These results indicate that while the SML has chosen the use of one or two ISO methods to standardise soil data collection across Europe, many SMSs rely on alternative methods. While the SML has chosen the use of one or two ISO methods per property to standardise data collection across Europe, many SMSs rely on national alternative protocols. These methods should now be compared to evaluate their degree of comparability.

3.3 | Comparative Analysis of Data Accessibility in Relation to the SML

The SML requires Member States to make monitoring results publicly accessible as aggregated data. Among the reported SMSs, 54% (12 out of 22) of the reported SMSs currently provide freely accessible data as aggregated data (Table 1). Data from five SMSs (Austria, both Czech Republic SMSs, Italy_Lombardia, and Switzerland) can be obtained upon request, while five SMSs (Belgium_Flanders, Denmark, Finland, Germany_BD, and the Netherlands) either restrict access or do not offer it at all. Notably, LUCAS Soil offers free access to most data, though access to contaminant-related data remains restricted.

3.4 | Experts' Feedback on SMS Adaptation and Collaboration

Most experts (with the exception of three) were unwilling to make substantial changes to their established SMS protocols, citing the rigidity of long-standing SMSs and the need to preserve historical data comparability. However, 20 out of 21 experts agreed to carry out double sampling exercises to compare their national protocols with LUCAS Soil, and 11 indicated openness to adding new monitoring sites (e.g., to improve spatial coverage) or including new measurements (e.g., biodiversity). Such actions would increase costs, and as highlighted by seven experts, it is already difficult to maintain existing SMSs due to budgetary constraints.

4 | Discussion

4.1 | Current SMS Practices vs. SML Requirements

Most European countries have established one or more SMSs, but significant differences in sampling strategies and protocols make results difficult to compare between countries (Bispo et al. 2021). These differences are shaped by national priorities, environmental conditions, different opinions on the scientifically best sampling design and analytical methods, and resource constraints, reflecting the unique contexts of each SMS design. While some SMSs monitor a broad range of soil properties, others are limited to specific properties, such as soil organic carbon, pH, or nutrients, leaving other critical soil health aspects unaddressed. This variability highlights disparities in priorities and capabilities among SMSs, as well as potential gaps in monitoring soil health.

The extent to which SMSs reflect the principles proposed in the SML varies depending on the specific criteria evaluated (Figure 4), with LUCAS Soil being the SMS most comparable to the SML framework. This similarity is unsurprising, given that the SML was partially built upon the methodology developed by LUCAS Soil. Other SMSs show greater or lesser divergence from the SML framework, depending on the criteria. For instance, within sampling strategies, the highest similarity is observed for composite sampling and information to be recorded, with most SMSs already meeting or exceeding the SML's requirements. However, challenges are more apparent for sampling depth, with many SMSs not sampling the proposed depth of 30 cm. This issue could be addressed if countries agree to sample an additional depth to reach 30 cm (e.g., by collecting both 0–20 and 20–30 cm layers). For soil properties measured, while certain key indicators like soil organic carbon are widely monitored, most SMSs do not measure all required properties, or do not fully use the SML's recommended methods. The observed variability highlights the need to address key gaps and inconsistencies between SMSs and the upcoming SML. Harmonizing will require balancing the development of common monitoring approaches with the need to respect and adapt existing SMSs, as only 3 out of 21 experts expressed willingness to make substantial changes to their current protocols.

4.2 | Spatial Coverage Challenges

To improve spatial coverage, many experts showed openness to adding new monitoring sites. The spatial distribution of sampling sites is crucial for capturing representative soil health data (Wadoux et al. 2024). The SML requires sampling points to reflect the variability of soil properties within soil units, which are subsets of broader soil districts. However, while the SML also limits error to 5%, it provides no specific guidance on the number of points required per soil unit. This is understandable, as such guidance would need to account for soil and land use variability, which can differ significantly between regions and countries. Given the variability in soil unit and soil district sizes across countries, setting a universal threshold may not be practical or meaningful.

Grid-based sampling approaches, employed by several countries, raise further questions about whether such designs can be adapted to meet the SML's stratification requirements. The example of France and the Czech Republic illustrates these challenges, with France highlighting the difficulties posed by high pedo-climatic diversity (Minasny et al. 2010) and the Czech Republic demonstrating the benefits of a dense sampling network. France's RMQS network currently monitors 2241 points across 13 administrative regions (NUTS level 1, considered here as soil districts). Assuming an average stratification of 14 soil types and 3 major land uses, this results in:

$$\text{Number of soil units} = 13 \times 14 \times 3 = 546$$

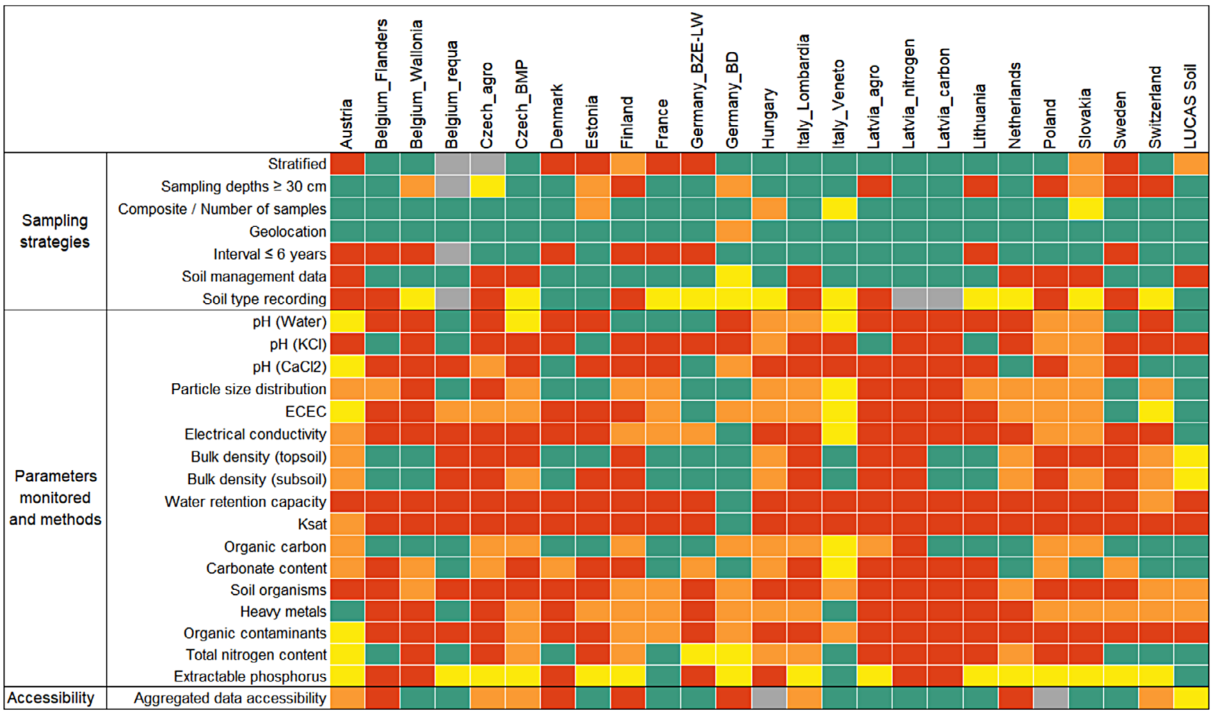

FIGURE 4 | Similarities of SMSs with the SML across sampling strategies, soil properties monitored, methods, and data accessibility. Colours indicate levels of similarity: Green (very high similarity), yellow (high similarity), orange (moderate similarity), red (low similarity), and gray (no information).

Given 2241 total points, this corresponds to an average of just 4 points per soil unit, which is insufficient to adequately capture soil variability. In contrast, the Czech Republic's Agrochemical Soil Testing Network, focused on agricultural soils, samples approximately 420,000 points across 14 administrative regions. With 6 soil types and 1 primary land use per region, the Czech Republic's SMS supports 84 soil units, averaging over 5000 points per unit. In Denmark, the national SMS is based on a 7×7km grid covering the entire country, yet it does not incorporate the stratification principles required by the SML. Greve et al. (2024) evaluated its suitability under several stratification scenarios, revealing that only 30% of national sites and 21% of LUCAS Soil 2018 samples meet the SML's criteria. Addressing these gaps could follow two complementary approaches: adding new points to improve the representation of soil units, integrating LUCAS points to support harmonization efforts, or a combination of both.

4.3 | Harmonization Opportunities

Most SMSs differ from the proposed SML guidelines in terms of sampling procedures, parameter selection, and measurement methods, making it challenging to compare results across SMSs. One way to address this challenge is through the development of transfer functions between laboratory methods of the same soil property and between sampling protocols. These can be derived by a double sampling campaign, where soil samples are collected and analyzed following both the LUCAS protocol and (if different) the SMS-specific protocol, as already done in Switzerland and Austria (Fernández-Ugalde et al. 2020; Baumgarten et al. 2021). This is complemented by double analysis, in which the samples are analyzed using both the SMS-specific methods and the LUCAS methods for the various properties. This approach enables the derivation, testing, and validation of transfer functions, which can be used to convert results obtained with one method into an equivalent result for another. Transfer functions were established for several properties, for example, pH, organic carbon content, particle size distribution, and phosphorus levels (Arrouays et al. 2015; Kabała et al. 2016; Hu et al. 2021). Note that such transfer functions may also introduce substantial uncertainties in the results, depending on the chosen equations (Steinfurth et al. 2021). The variation in laboratory quality across the EU further complicates the comparability of soil data. To address this, the SML proposes the inclusion of minimum requirements for quality control in laboratories analysing soil samples.

Another potential method to harmonise soil health assessments across SMSs, even if not yet included in the SML requirements, is the use of scores. This approach, used in countries like the United States and Canada, involves translating soil measurements into scores based on the relationship between the soil indicators and relevant soil functions (Fine et al. 2017; Amgain et al. 2022; Gauthier et al. 2023; Poppiel et al. 2025). These individual scores are then aggregated into an overall soil health score, providing an evaluation of soil health. Importantly, scoring systems can be adapted to local contexts by incorporating regional variations in soil types, pedo-climatic conditions, land use, and management practices. In Europe, initiatives like EJP SOIL are testing data-driven scoring systems based on the statistical distribution of soil data at national and regional scales. While still under evaluation, this approach holds potential for improving comparability across SMSs, aligning with the SML's requirements, and accommodating local specificities. However, scoring functions can also introduce more discrepancies among different datasets.

4.4 | Balancing Data Availability and Privacy

Data accessibility remains a significant challenge, with limited consensus on standards for ensuring interoperability and broad availability. This issue is compounded by the fact that much of the data is georeferenced and, in several countries, can be classified as personal data subject to General Data Protection Regulation (GDPR) constraints (Fantappiè et al. 2021; Cornu et al. 2023). While such restrictions could be avoided by aggregating and disseminating data at the soil unit level (e.g., reporting a mean value for a whole soil unit instead of all georeferenced individual measurements) to ensure both privacy and accessibility, as proposed in the SML, it is important to note that many applications of soil monitoring data require access to geographically precise, non-aggregated data (e.g., for digital soil mapping application). An option could be to provide the data with approximate coordinates and an uncertainty on these coordinates, making sure that the level of uncertainty is sufficient for the sampling location not to be identified.

5 | Conclusion

This study highlights the significant variability in the design and implementation of SMSs across countries participating in EJP SOIL. While this diversity reflects national priorities, environmental conditions, different scientific opinions on the most appropriate sampling design and analytical methods, and resource constraints, it also poses challenges for harmonizing soil monitoring efforts and addressing the requirements of the upcoming SML. Key differences were identified in the sampling design and monitored properties, which hamper the comparability of results and the ability to monitor soil health effectively at the EU level (Froger et al. 2024).

Despite these challenges, several opportunities exist to harmonise SMS with the upcoming SML. For existing SMSs, harmonization can be pursued by adding new monitoring points to address gaps in spatial coverage, integrating scoring systems for soil health evaluation, or developing transfer functions to reconcile methodological differences. For new descriptors included in the SML but not yet routinely measured in existing SMSs (e.g., biodiversity indicators, pesticides, PFAS, and microplastics), there is a clear opportunity to define standard sampling and measurement protocols from the outset. Finally, the same occurs for countries where no SMS currently exists; the SML can serve as a standard for designing new systems.

This study focuses on SMSs primarily targeting agricultural soils. However, some countries have additional monitoring networks dedicated to other land uses and soil-related processes. Including these SMSs, as well as SMSs from EU Member States outside EJP SOIL, will enhance the complexity of harmonizing existing data to meet the requirements of the SML framework. Additionally, although this study evaluates several key soil properties monitored by SMSs, it does not cover certain aspects explicitly recommended by the SML, such as soil erosion and soil sealing. These soil threats are crucial for meeting the comprehensive objectives set by the SML. Future research should assess the capacity of existing SMSs to monitor these processes.

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Data Availability Statement

The data that support the findings of this study are openly available in Recherche Data Gouv at https://doi.org/10.57745/7Y1SKR.

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